Multi-Technique Studies of Ionospheric Plasma Structuring

Sunanda Basu
Center for Space Physics
Boston University
725 Commonwealth Avenue
Boston, MA 02215
phone: (202) 404-1290 fax: (202) 767-9388 email: sbasu@bu.edu

Award Number: N00014-03-1-0593

LONG-TERM GOALS

Understanding physical processes that leads to plasma structuring in the equatorial, mid and high-latitude ionosphere. Identifying the effects of such variability, generally known as ionospheric space weather, on the operation of various communication, navigation and surveillance systems.

OBJECTIVES

Establish major drivers that lead to structured ionospheric plasma in equatorial, mid and high-latitude regions. Investigate cascading of plasma structuring from large (~ hundreds of km) to small scales (~ tens of m), which cause outages in space-based communication and GPS-based navigation systems.

APPROACH

Analysis of GPS phase fluctuations in conjunction with regional total electron content (TEC) maps, in-situ measurements of sub-auroral polarization streams (SAPS) and auroral convection from several DMSP spacecraft and dynasonde measurements at the Bear Lake Observatory obtained during the intense magnetic storm of November 8, 2004, have indicated the tremendous impact of large ionospheric velocities on GPS-based navigation systems within the mid-latitude region in the North American sector. The major difference between this superstorm and the others observed during the October-November, 2003 events is the absence of appreciable storm-enhanced density gradients, with the mid-latitude region being enveloped by either the auroral oval or the ionospheric trough within which the SAPS were confined during the local dusk to nighttime hours. This shows that it is possible to disable GPS-based navigation systems for many hours even in the absence of appreciable TEC gradients, provided an intense flow channel is present in the ionosphere during nighttime hours. The competing effects of irregularity amplitude DN/N, the background F-region density and the magnitude of SAPS or auroral convection are discussed in establishing extent of the region of impact on such systems.
The PI is the primary person working on this problem with scientific colleagues providing the scintillation and DMSP data analysis (Keith Groves, Fred Rich of AFRL and Santimay Basu, Eileen MacKenzie and Pat Doherty of Boston College).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **Multi-Technique Studies Of Ionospheric Plasma Structuring**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Boston University,Center for Space Physics,725 Commonwealth Avenue,Boston,MA,02215**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

WORK COMPLETED

The above analysis has been completed and a manuscript is being prepared for publication in the Special Section of Journal of Geophysical Research on the NASA/LWS related magnetic storm papers. Two presentations on the comparison of several storms and their impacts on GPS navigation were made at the NASA/LWS Meeting at the Florida Institute of Technology in March, 2007 and the International Meeting on Beacon Satellite Studies at Boston College in June 2007.

RESULTS

Background.

The effects of intense magnetic storms on the mid-latitude ionosphere have recently been extensively documented [Basu et al., 2005 and references therein]. In the North American sector, the focus has been primarily on the rapidly sunward convecting plumes of enhanced solar-produced ionospheric densities seen in GPS TEC (total electron content) maps. These high-TEC plumes of ionization are seen in the pre-midnight and afternoon sector at the equatorward edge of the main ionospheric trough and stream sunward carried by the low-latitude edge of the sub-auroral disturbance electric field known as the sub-auroral polarization stream or SAPS. Combining ground and space-based thermal plasma imaging techniques, Foster et al. [2002] demonstrated that one such ionospheric SED plume observed during the intense magnetic storm of March 31, 2001 mapped into the low-altitude signature of a plasmasphere drainage plume associated with the stormtime erosion of the outer plasmasphere. Since that time, Keskinen et al. [2004], using several mid-latitude experimental studies, developed a model for small-scale ionospheric structure in the SAPS-driven density trough during magnetic storms. Earlier, Basu et al. [2001] had shown that intense VHF amplitude scintillations and GPS phase fluctuations were observed at mid-latitudes during magnetic storms that occurred in September and October, 1999 when transient magnetospheric electric fields penetrated into the plasmasphere during the evening hours. Analysis of VHF amplitude scintillation, GPS phase fluctuation and ionosonde measurements in conjunction with regional GPS total electron content (TEC) maps, ground-based observations of daytime aurora and TIMED GUVI images obtained during the large magnetic storms of October 29-31, 2003, have indicated that there are two distinct plasma processes that give rise to mid-latitude ionospheric irregularities. One is associated with auroral plasma processes and the other with storm enhanced density (SED) gradients which have been shown to be the ionospheric signatures of plasmaspheric tails [Foster et al., 2002, 2005].

Analysis of GPS phase fluctuations in conjunction with regional total electron content (TEC) maps, in-situ measurements of sub-auroral polarization streams (SAPS) and auroral convection from several DMSP spacecraft and dynasonde measurements at the Bear Lake Observatory obtained during the intense magnetic storm of November 8, 2004, have indicated the tremendous impact of large ionospheric velocities on GPS-based navigation systems within the mid-latitude region in the North American sector. The major difference between this superstorm and the others observed during the October-November, 2003 events is the absence of appreciable storm-enhanced density gradients, with the mid-latitude region being enveloped by either the auroral oval or the ionospheric trough within which the SAPS were confined during the local dusk to nighttime hours.

In the rest of this paper, we present and discuss the characteristics of this new genre of GPS TEC perturbations driven by large mid-latitude flows rather than by the sharp organized density gradients associated with SEDs. Simultaneous “snapshots” of the cross-track velocities from several DMSP satellites are compared with the ionospheric signature of the plasmapause and their joint evolution in determining the impacts on the GPS TEC measurements through phase fluctuations and subsequent loss of lock of the GPS receivers. Using these multi-technique measurements, we try to understand the varying degree of impacts on the WAAS system during the main phase of the storm by following the dynamics of the magnetospheric boundaries such as the auroral oval and the plasmapause. It is hoped that the results of this study will provide inputs to theorists interested in pursuing large velocity driven instability processes at the meso/micro scales, as well as magnetosphere-ionosphere coupled model studies at global/regional scales.

Discussion.

As in the Su. Basu et al., (2005) paper, the major source of data comes from the dense network of GPS TEC stations in North America. TEC maps are generated by combining data from approximately 500 dual-frequency GPS receivers, made publicly available through a variety of sources. The GPS data are converted from line-of-sight to vertical TEC by assuming a thin-shell ionosphere at 350 km. Five-minute average TECU values are binned onto a 1 degree latitude/longitude grid; one TECU represents 10*16 electrons/m2. For computing TEC fluctuations, we use a subset of about 250 GPS dual-frequency stations to compute structuring at tens of km scales. TEC measurements made every 30 seconds are differenced to obtain one-minute values of TEC fluctuations. Within every 15-minute UT interval at each station, the maximum absolute value of TEC fluctuation along an individual satellite track is found from the one-minute values, after imposing a minimum 30-degree elevation angle cut-off to reduce multi-path effects. This maximum value is then assigned to the 350-km intersection closest to the center of the region covered in 15 minutes; intersections in a 15-minute interval generally move less than one degree in latitude and longitude at mid- and low-latitudes. Similar data from all stations are collected into 2 degree latitude-longitude bins to produce a single 15-minute map of TECU/min. It is important to note that, in general, irregularity scales covered by TEC fluctuations depend on irregularity motion during the 30-second measurement interval, because in a power law environment the irregularity amplitude increases with scale length. With irregularity velocities on the order of 1 km/s, a scale-length of 60 km will be covered during a 30 second measurement (the half-Nyquist interval). During these storms, we used space-based in-situ measurements of plasma densities, cross-track velocities, and auroral particle precipitation from several DMSP satellites in various dusk-time orbits at 840 km. These types of measurements have been widely used to elucidate the evolution of plasma density, velocity and demarcation of magnetospheric boundaries during magnetic storms.

The diagram below shows cross-track E-W velocities from parts of two DMSP F-15 and F-16 orbits crossing the US around 00:50 UT on Nov 8, 04. These orbital tracks are superimposed on a TEC map, with the data averaged over 00:50-:0055 UT.

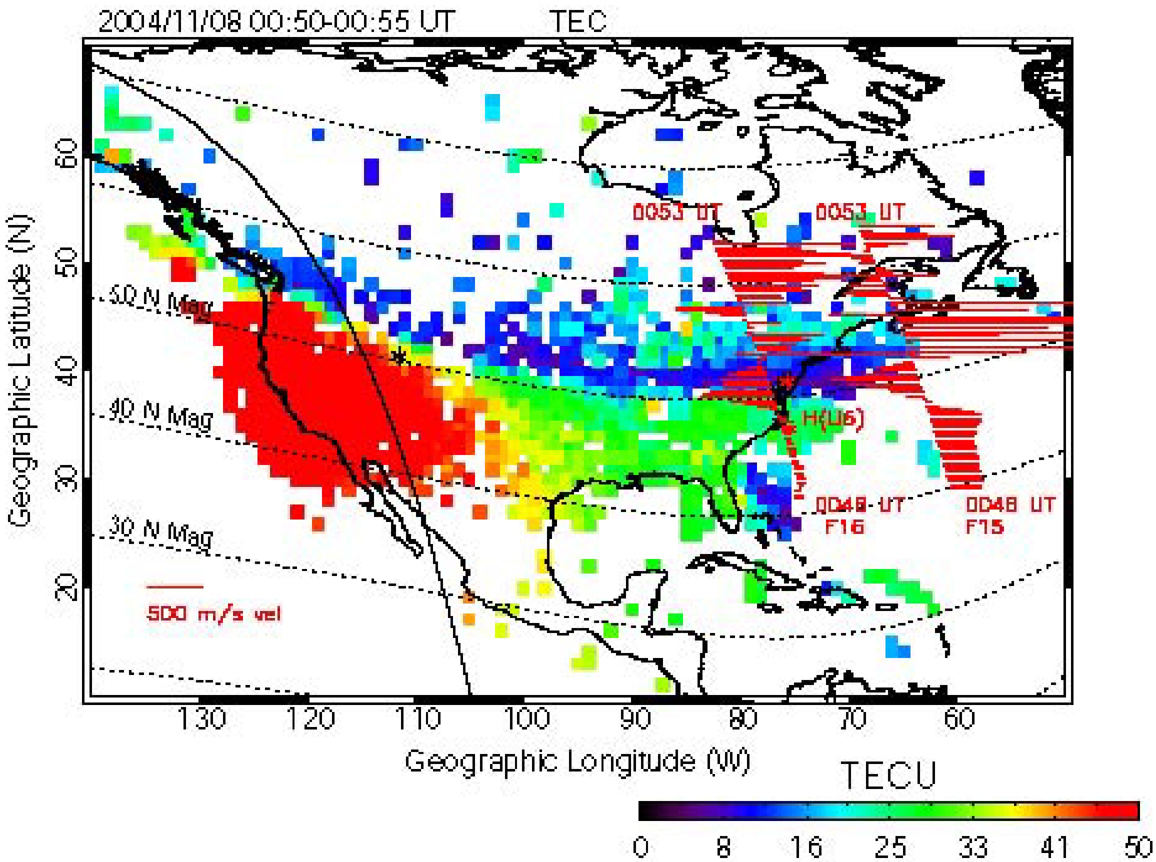

Figure 1 – Two DMSP tracks superposed on a TEC map of the US showing large SAPS and auroral velocities within and poleward of the trough at 00:50 UT on Nov 8, 04

A prominent signature of the trough is seen to be developing across the entire country poleward of 50 degrees geomagnetic latitude. This location appears to be the seat of the large velocities. The higher velocity region poleward of the trough is associated with the aurora as observed by the particle detectors on the same DMSP satellites. The high TEC region is bounded by the terminator indicated by the solid black line on Figure . There is perhaps a weak SED plume extending from the westernmost region of the US but it is clear from Figure 2 that the enhanced density plume and the gradients associated with it cannot be responsible for the WAAS disruption over almost the entire country shown by the yellow and red areas in Figure 2. This diagram provides color-coded regions of Grid Ionospheric Vertical Error at 00:50 UT as shown by the key to the right. WAAS can only operate in regions of GIVE less than 6m (Doherty et al., 2004). The WAAS system was down for 12 hours on this day as an aid to instrumented aid for aircraft using a single-frequency GPS in its approach to US airports.

We thus put forward the hypothesis that the large velocities in the SAPS and auroral regions create very large phase fluctuations within the 30 sec measurement period with the result that the GPS receivers lose lock. This leads to unacceptably large errors and gaps in the data so that the WAAS system cannot operate.

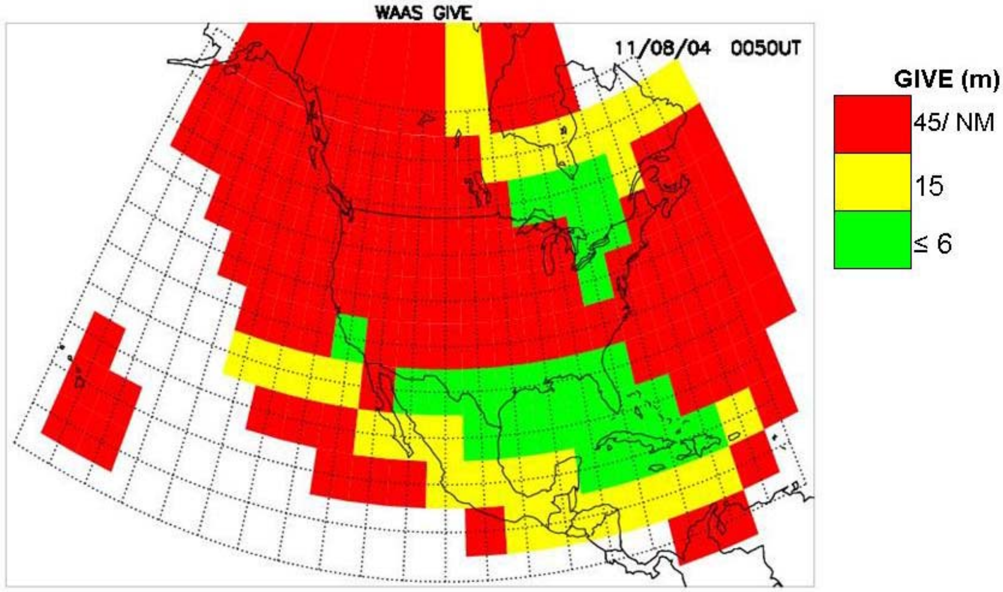

Figure 2 – The GIVE map for the WAAS system at 00:50 UT on Nov 8, 2004

IMPACT/APPLICATIONS

Thus we have been able to isolate a new phenomenon which causes a deleterious effect on a very important operational system affecting both civilian and military users. Hitherto, only the enhanced density feature known as SED was viewed as the culprit. The SEDs occur earlier in the afternoon, whereas at dusk the trough, the ionospheric signature of the plasmapause, and the auroral oval move equatorwards enveloping most of the CONUS. Thus both enhanced densities and/or velocities are the major factors in disabling WAAS depending on the LT of storm main phase. This coupling of the entire magnetosphere-ionosphere system makes the understanding and prediction of magnetic storm impacts so challenging. However, since the impacts are so severe on DoD and civilian communication and navigation systems, it is worth the effort!

RELATED PROJECTS

Coordinated multi-technique measurements were conducted in September, 2006 in support of COSMIC satellites launched in April 2006. These early measurements were organized to take advantage of the clustering of satellites in the constellation generally referred to as “beads on string” configuration. This configuration only occurs during the early phase when the satellites are around the launch altitude, approximately 500 km, before they are finally deployed at 800 km altitude. The NRL TIP observations of nighttime 135.6 nm emission provide the features of the equatorial anomaly, namely the ionization density at the crests, the crest to trough density ratio, the latitude separation of the crests and their asymmetry. Major ground-based support was provided by incoherent scatter radars at Jicamarca and Kwajalein, the TEC network in the South American sector and scintillation measurements from nearby SCINDA sites. All-sky imaging photometer observations were also made from Kwajalein to provide context for the COSMIC/TIP overflights. There has been considerable analysis of these space and ground-based observations and a joint paper will be presented at the Fall

AGU 2007.meeting discussing upward vertical drift variation and TIP intensity variation associated with peaks of the equatorial anomaly at dusk as a function of longitude.

REFERENCES:

Basu, Su., S. Basu, C.E. Valladares, H.C. Yeh, S.-Y. Su, E. MacKenzie, P.J. Sultan, J. Aarons, F.J. Rich, P. Doherty, K.M. Groves, and T.W. Bullett, Ionospheric effects of major magnetic storms during the International Space Weather Period of September and October 1999: GPS observations, VHF/UHF scintillations, and in situ density structures at middle and equatorial latitudes, *J. Geophys. Res., 106,* 30, 389, 2001a.

Basu, Su., S. Basu, J.J. Makela, R.E. Sheehan, E. MacKenzie, J.W. Wright, M. Keskinen, D. Pallamraju, L.J. Paxton, and F.T. Berkey, Two components of ionospheric plasma structuring at mid-latitudes observed during the large magnetic storm of October 30, 2003, *Geophys. Res. Lett., 32,* L12S06, doi:10.1029/2004GL021669, 2005.

Doherty, P., A. J. Coster, and W. Murtagh, Space Weather Effects of October - November, 2003, *GPS Sol.*, *8*(3), doi:10.1007/s10291-004-0109-3, 2004.

.Foster, J. C., P. J. Erickson, A. J. Coster, J. Goldstein, and F. J. Rich, Ionospheric signatures of plasmaspheric tails, *Geophys. Res. Lett.*, *29*(13), 1623, doi:10.1029/2002GL015067, 2002

Foster, J. C., et al., *J. Geophys. Res.,A09S31, doi :10.1029/2004JA010928*, 2005.

Keskinen, M. J., S. Basu, and S. Basu, Midlatitude sub-auroral ionospheric small scale structure during a magnetic storm, *Geophys. Res. Lett.*, *31*(9), L09811, doi:10.1029/2003GL019368, 2004.

PUBLICATIONS

Response of the equatorial ionosphere to prompt penetration electric fields during intensemagnetic storms" by S. Basu, Su. Basu, F.J. Rich, K.M. Groves, E. MacKenzie, C. Coker, Y. Sahai, P.R. Fagundes, and F. Becker-Guedes, Journal of Geophysical Research, Vol 112, A08308, doi10.1029/2006JA012192, 2007

HONORS

Sunanda Basu was invited to deliver a talk on New Science Initiatives with Beacon Satellites at the International Beacon Satellite Symposium at Boston College on June 11, 2007.